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RATIONALE FOR STRUCTURAL INSPECTIONS

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SUMMARY

During the past few years, methods have been developed to predict the reliability of aircraft structures. They depend upon inspection effectiveness which, in turn, depends upon structural complexity, quality, and the percentage of the structure inspected. Reliability can be enhanced by choosing materials properly, designing damage-tolerant structures, and increasing inspection frequency. And, for fleet operations, costs can be minimized through proper inspection schedules, and enhanced reliability can be compatible with minimum cost. The methods are derived from a combination of probability theory and engineering equations.

INTRODUCTION

During the past few years, methods have been developed to predict the reliability of aircraft structures. The methods are derived from a combination of probability theory and engineering equations. Their earliest application was to military aircraft operations, where the military urgently needed ways to prolong fleet life and to ensure that enough aircraft were always available for use. The purpose of this paper is to acquaint the operators of the commercial fleet with these methods and how they have been used to improve reliability and reduce the cost of operations.

The discussions in this paper are not meant to serve as "cookbook" guides to application, but only to synopsize some of the methods applicable to commercial fleet operation. Those who wish to apply these methods to their own fleet operations are urged to consult the references which discuss, in more detail, how the methods are used and what data are needed as input for the analyses.

INSPECTION

Reliability methods depend upon inspection. Figure 1 shows a typical inspection problem encountered in the laboratory. The specimen, about 5.5 cm wide, is subjected to repeated loads in tension. If a crack grows, it will start at the small drilled holes and will propagate across the width. Cracks 0.1 mm long can be found easily for two reasons: the inspector knows where to look, and the specimen is accessible.

Figure 2 is a photograph of an aircraft wing box, a much harder inspection problem. Sometimes the inspector knows where to look (for example, if he is responding to an airworthiness directive), but, even so, cracks can occur anywhere. And a few parts of the structure are inaccessible to anything except a teardown inspection. Practical inspection and reliability methods must take into account the possibility of random flaw locations, multiple flaws, and area inaccessibility.

The reliability after inspection depends upon how well a crack can be detected. Figure 3 (refs. 1 to 3) shows some typical data for the probability of detection (solid lines). In contrast, the dashed lines show some empirical fits; they can be adjusted analytically to match reasonably smooth experimental curves fairly well. In general, the probability of detection is larger for longer cracks. Ultrasonics and dye penetrant inspections are more sensitive than X-rays, but to use them the area must be accessible. X-rays are used for inaccessible areas, but the radiation source must be positioned directly over the crack. The data in figure 3 are from detectability tests generally under laboratory conditions. Part of the reason that the experimental curves are not smooth is the paucity of data, even though these curves were obtained during an extensive and well-planned program. The unevenness of the curves illustrates a point: not much data exist yet about the inspection process, a process that includes both apparatus and inspector. A statistician, of course, would want enough data points to establish 90-percent or 95-percent bounds on the curves.

Figure 4 (ref. 4) shows one of the empirical curves. It has several features. First, if the crack is short enough, it cannot be found (detectability is 0). Second, there is a crack length that corresponds to some given detectability; here, cracks of length a and longer can be found at least 90 percent of the time. And finally the curve may never reach 1.0 because, for various reasons, even long cracks are occasionally overlooked. Sometimes the curve may not be completely defined, but for some uses, only the crack length at some percent of detectability needs to be known. Such a simple case is considered first.

With these aspects in mind, figure 5 (ref. 5) relates the reliability after inspection to the probability that the part was crack free before inspection. Reliability here has a specific meaning: a part that has passed inspection has passed because it was thought to have been crack free. Reliability after inspection is the probability that the part actually is crack free. Detectability is a parameter for the various curves. Here the inspector knows where to look, and only must decide whether one crack of some given length (such as 4 mm) or longer is, or is not, present. This is a simple inspection case. Note that all the curves lie above the no-inspection line, showing that inspections always enhance reliability. And, because they increase monotonically, high initial quality (reliability before inspection) always enhances final reliability.

However, quite frequently a crack or cracks can appear at random locations (as, for example, in the structure in fig. 2). And, in such a case, the actual number of cracks is not known. Figure 6 shows the reliability after inspection as a function of the detectability for the case where the actual number of cracks in a given piece is a random number, Poisson distributed. The mean (or average) number of cracks per piece before inspection is the parameter shown beside each curve. Cracks might be anywhere in the structure. Reliability is significantly enhanced if detectability is high. (High detectability implies an effective inspection procedure.) If a part contains, on the average, 10 cracks before inspection, detectability must be very high if the part is to be reliable after inspection.

Figure 7 is like figure 6, except that figure 7 applies to a case where 25 percent of the structure is inaccessible for inspection. Because there is a chance that some of the randomly located cracks might be in the uninspected region, the curves in figure 7 are lower than the curves in figure 6. Note in particular that 100 percent reliability cannot be attained, even if cracks are 100 percent detectable. At mean of 1 flaw per part the highest that reliability can be is about 0.78.

Up to this point, unreliability has been defined as having an overlooked crack; unreliability has not necessarily meant that a part will fail. (Ways to build crack-tolerant structures, where the seriousness of small undetected cracks is minimized, are discussed subsequently.) Consider the case where an overlooked crack grows longer under the influence of stress changes due to gust and maneuver loads. Reliability is redefined to mean that any crack present will not grow to be "critically long" before the next inspection. A critical length may be the length at which the structure no longer supports limit loads, or some shorter length, perhaps one that only makes passengers nervous if they see it. Whatever the chosen definition, critical length is some fixed value that must not be exceeded, and the structure is reliable only if the critical length is not reached.

Figure 8 (ref. 4) illustrates a distribution function that represents crack lengths. The solid curve indicates that short cracks are likely to occur much more often than long cracks do. After some initial flights the cracks grow, so that the dashed line represents the new crack length distribution. During inspection, the longer cracks are likely to be discovered and fixed, so that the dashed-dot line represents the distribution after inspection. The dashed-dot line fairs into the dashed curve at the limit of detectability — shorter cracks are not detectable. During subsequent flights, unrepaired cracks continue to grow.

Figure 9 shows the results of an analysis that recognizes growing cracks. The two curves illustrate the relative impact of various inspection schedules. The abscissa is the frequency of inspection; it is the number of inspections scheduled during a period whose length is such that a just-detectable crack can grow to critical length. The two symbols have the following definitions: t_c is the time at which a crack just becomes critically long and t_d is the time at which the crack becomes long enough to be detectable (for example, detectable 90 percent of the time). The curve R_{02} illustrates the reliability for surviving one inspection period with no initial inspection. The curve R_{012} is for survival of one period with an initial inspection; it is higher because the extra inspection is likely to discover more cracks that could grow to critical length between inspections.

ENHANCING RELIABILITY

It is helpful of course, to know what size crack must be found to keep the structure reliable between inspections. Figure 10 shows "safe" crack lengths plotted against the normalized inspection frequency. First, look at the curve for a critical crack length a_c of 100 mm. At a frequency of two inspections during the normal period, all cracks shorter than 7.7 mm must be detected. On the other hand, if $a_c = \infty$ (in an infinitely tough material), an inspector must still find all cracks longer than 8.3 mm, so switching to a tough material does not help much when inspections are infrequent. For more frequent inspections tolerable crack lengths are longer, but also the curves separate. Tougher materials can help to alleviate an inspection detectability problem if inspections are frequent, if the structure remains strong even with moderately long cracks, then, of course, it remains reliable. Since a moderately long crack can be detected more easily than a short crack, the detectability problem is moderated, and the structure is more likely to be repaired before the crack becomes critically long.

Figure 11 (ref. 6) shows how the choice of material influences performance. For structures in tension, such as the lower wing surface, stress/density is a measure of the load-carrying ability per pound of structure. High values on the ordinate indicate efficient structures. The life requirement is the life of the aircraft, or, perhaps as in this discussion, the time between inspections. The initial flaw (crack) size is the length of a crack just a bit smaller than that which can be detected. D6ac steel is the most efficient of the three materials if very small cracks, for example, 1 mm, can be found. Titanium is best if a somewhat longer crack must be tolerated; but cracks grow relatively fast in titanium, so the useful life is not as long as for 2024-T3 aluminum which can tolerate much longer cracks than the other two materials can.

In addition to choosing the proper material, the structure itself can be made crack tolerant (ref. 7). Figure 12 is not only a graph of residual strength, it is also a sketch of a panel with riveted stringers. Only the right half of the panel is sketched; the panel is symmetric about the vertical center line (the ordinate). Only one-half of the crack is shown, it, too, is symmetric. Figure 12 shows how riveted stringers help to retain the load-carrying ability of a cracked plate. Here load-carrying ability is plotted against crack length. The dashed line shows the strength of a plate with no stiffeners. As the percentage of material in the stiffeners increases, so does the load-carrying ability. This is because the stiffeners pick up the residual load as the crack passes underneath. Some structures have integral stiffeners instead of riveted stiffeners; a panel with integral stiffeners has about the same crack tolerance as a panel without stiffeners because the stiffeners [illegible] crack.

Thus proper materials and construction enhance [illegible] longer cracks can be tolerated, and an inspector is [illegible] to find long cracks.

MINIMIZING COSTS OF OPERATION

Reliability methods can be applied to economy of fleet operation. Figure 13 (ref. 8) shows the cumulative cost of inspection and repair plotted versus design lifetimes. The data are for a fleet of fighter aircraft with a design life of 6600 flights. The aircraft are inspected every 2200 flights. The top curve is total cost, and the next is repair cost; the dash-dot curve is inspection cost. Repair cost is the major contributor to total cost. Note that the cumulative total cost and cumulative repair cost begin increasing rapidly after the aircraft has been in service for two lifetimes. Figure 14 is the same data for inspections scheduled every 1100 flights. It is cheaper to inspect and repair every 1100 flights, chiefly because cracks remain small and are cheaper to repair. For example, small cracks near holes can be fixed by reaming the hole, whereas larger cracks may lead to major rework. The lower repair cost more than offsets the larger inspection cost.

Of course, the cost of extremely frequent inspection might overwhelm the gain in repair cost, and consequently an optimum inspection frequency exists (ref. 9). Figure 15 shows how this optimum can be found. (Some commercial transport data were used in computing this figure.) The ordinate is the total operating cost, including the expected cost of failure of the aircraft, divided by the cost of failure. (The expected cost of failure is generally low, because it is the product of the cost of failure and the unreliability, and the unreliability is a very small number.) The cost of failure can include replacement cost, insurance losses, ancillary damage, lawsuits, etc. The abscissa is the number of scheduled inspections per design lifetime. The parameter for the various curves is the inspection cost divided by the cost of failure. Each curve has a minimum, located by the dashed line; at which the expected operating costs are minimized.

In figure 16 some data have been added to figure 15. The dot-dashed curve is the probability of failure, calculated by methods somewhat like those discussed previously. If operations are to be constrained to some value of unreliability, such as 10^{-3} (reliability of 0.999), then each aircraft must be inspected at least seven times during its design lifetime. Thus, for a parametric value of 10^{-3}, the aircraft must be inspected more often than it would have been to minimize expected operational costs. But for parametric values of 10^{-4} and smaller, the minimum cost number of inspections leads to reliability greater than 0.999. Thus, for certain values of the parameter, enhanced reliability and lower operational costs go together.

CONCLUDING REMARKS

To sum up, inspection effectiveness depends upon structural complexity, quality, and the percentage of the structure inspected. Reliability can be enhanced by choosing materials properly, designing damage-tolerant structures, and increasing inspection frequency. And, for fleet operations, costs can be minimized through proper inspection schedules, and enhanced reliability can be compatible with minimum cost.

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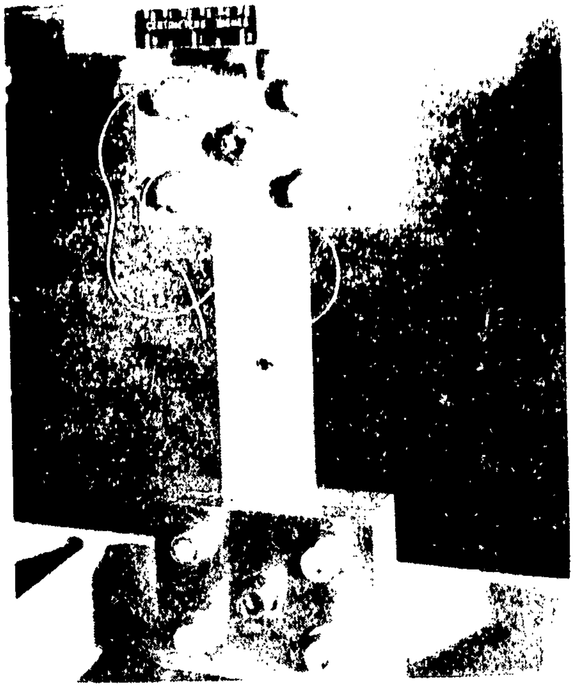


Figure 1.- Laboratory fatigue specimen.

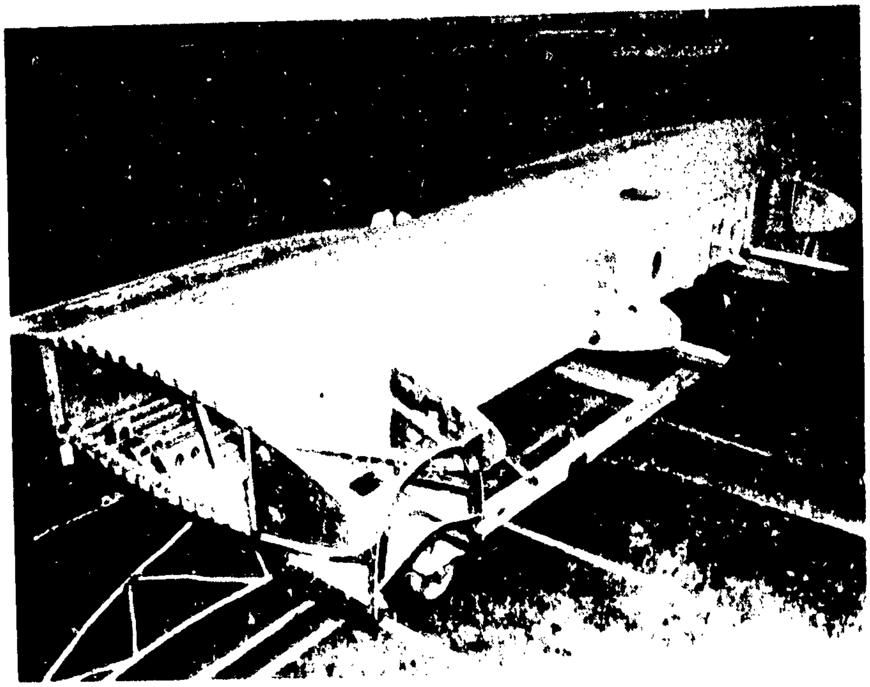


Figure 2.- Aircraft wing box.

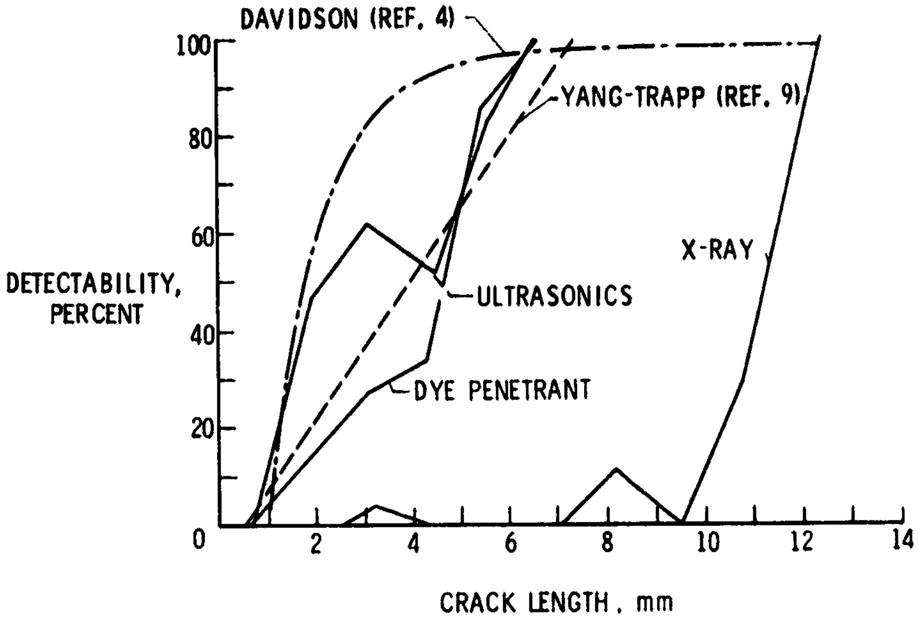


Figure 3.- Typical data and empirical curves for probability of detection (ref. 1). Empirical curves can be adjusted to fit experimental data.

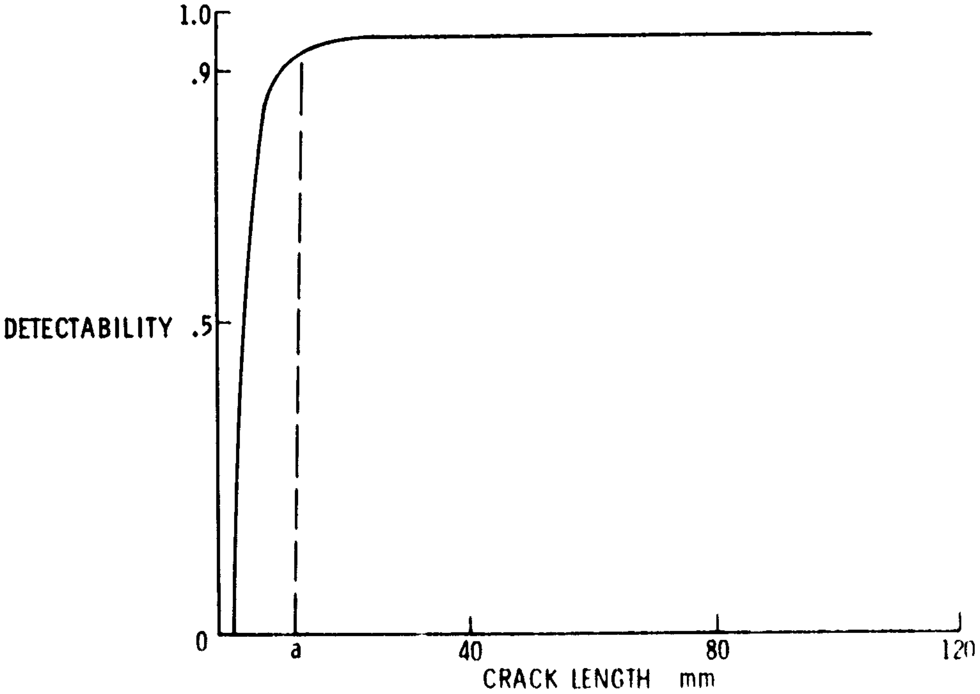


Figure 4.- An empirical curve for probability of detection.

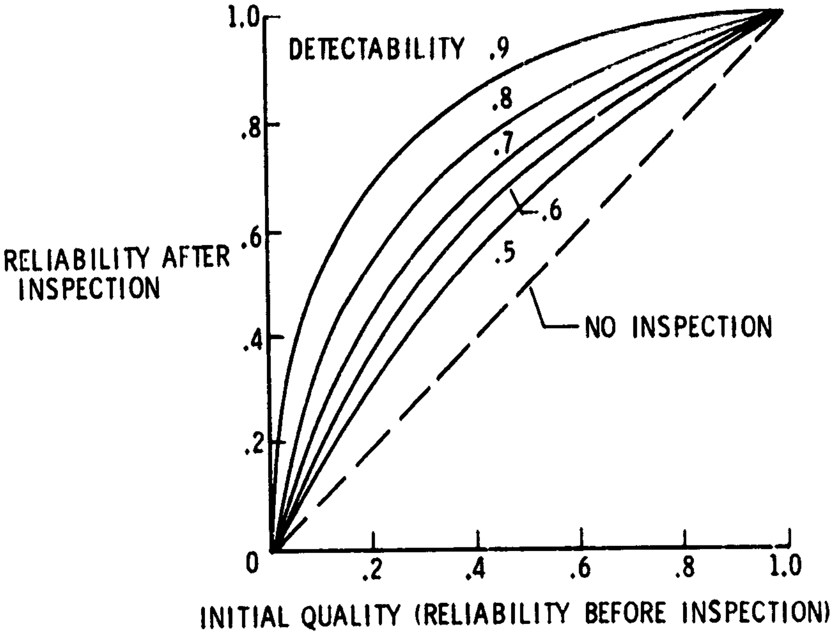


Figure 5.- Quality, detectability, and reliability. Crack site known.

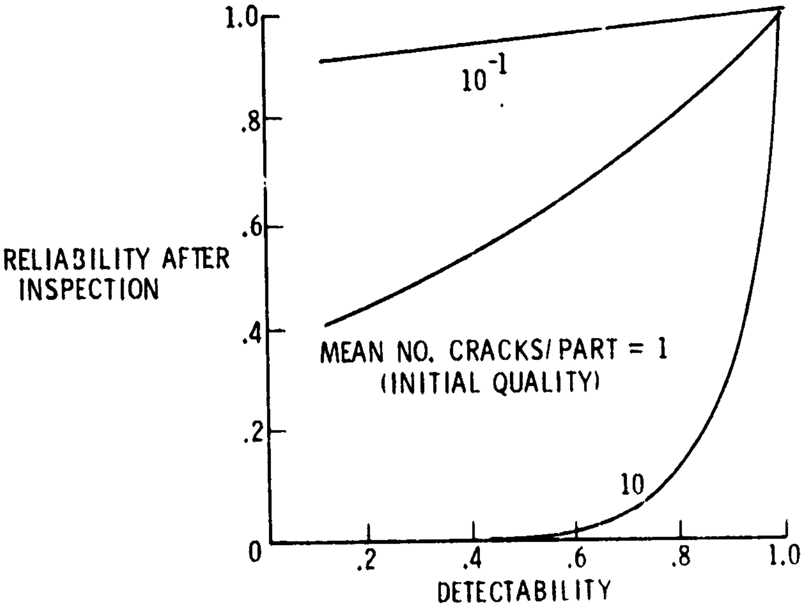


Figure 6.- Quality, detectability, and reliability. Randomly distributed crack sites; 100 percent of structure inspected.

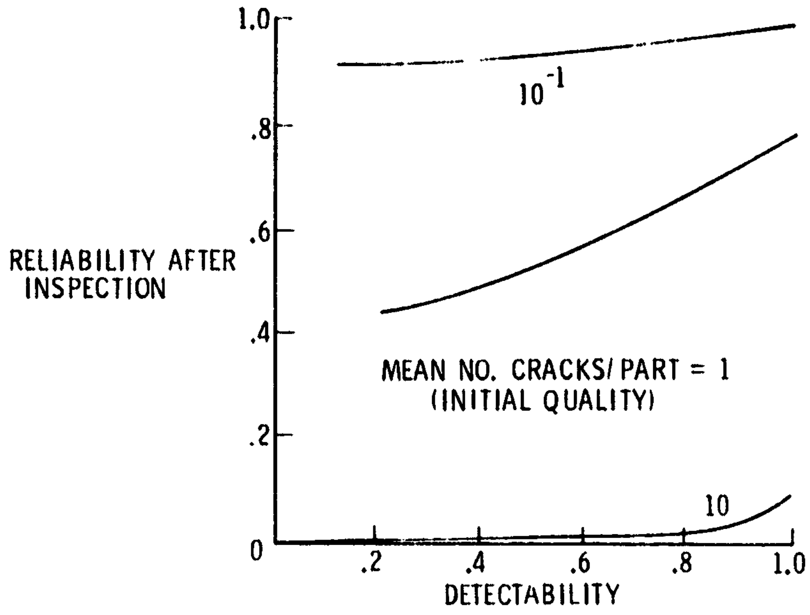


Figure 7.- Quality, detectability, and reliability. Randomly distributed crack sites; 75 percent of structure inspected.

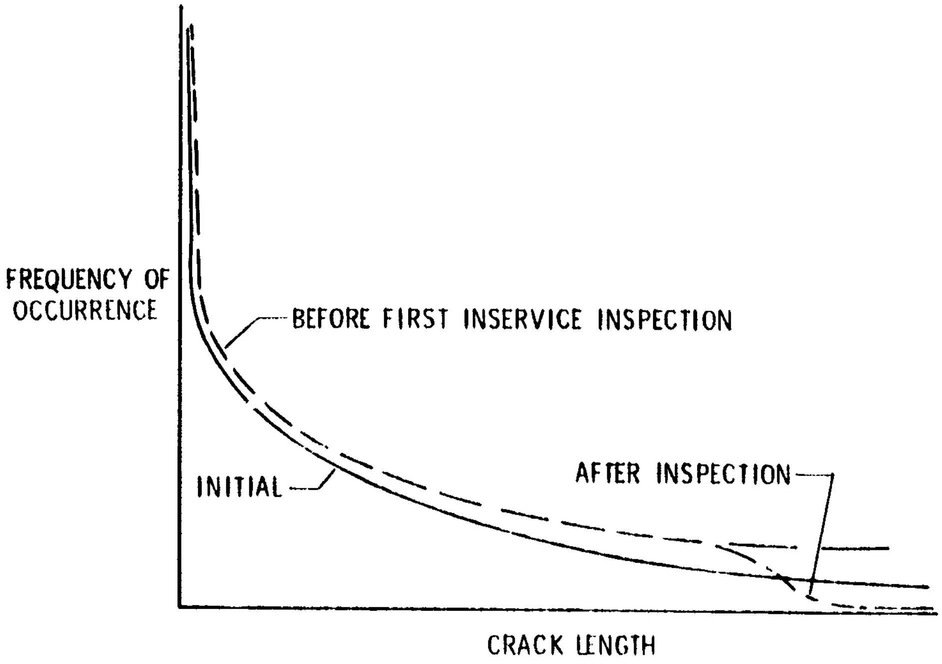


Figure 8.- Distribution functions for crack length.

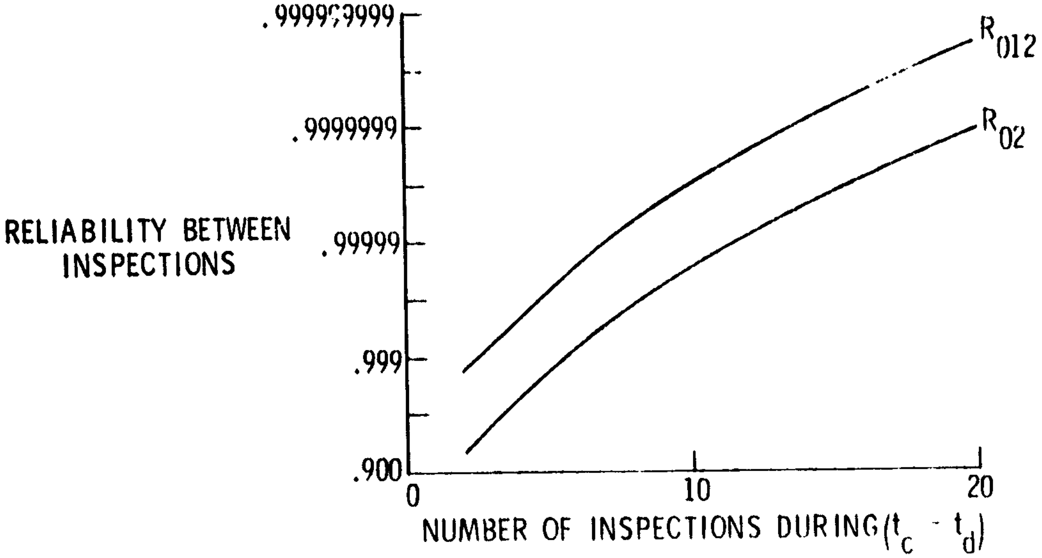


Figure 9.- Effect of various inspection schedules.

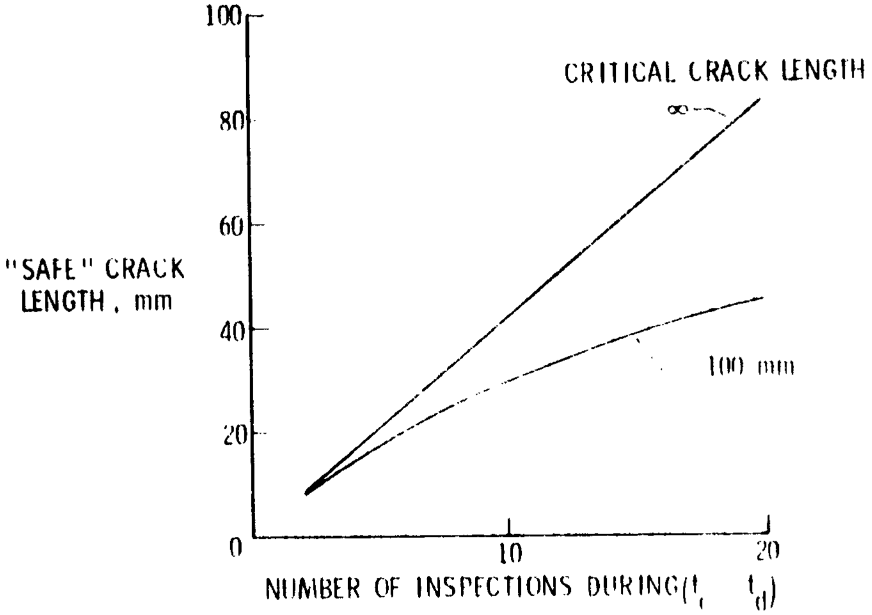


Figure 10.- "Safe" crack length and material toughness.

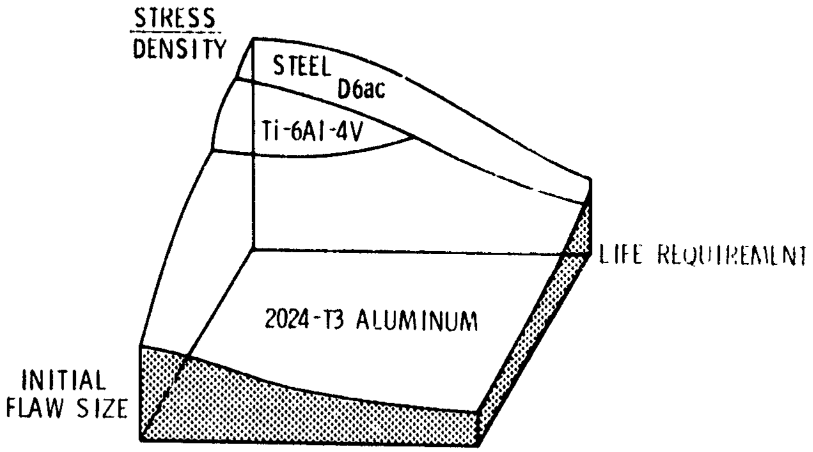


Figure 11.- Relative efficiencies of some aircraft materials.

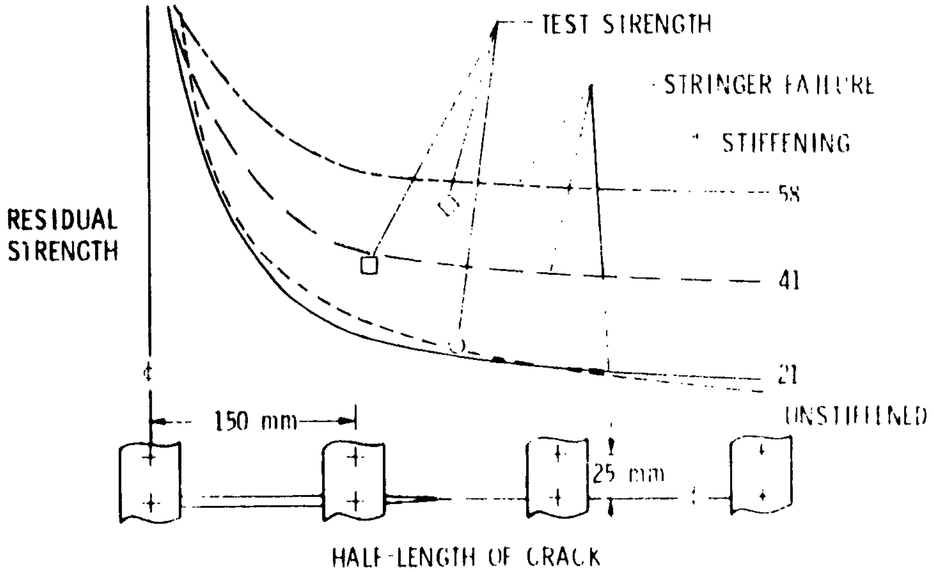


Figure 12.- Residual strength of panel with riveted stringers.

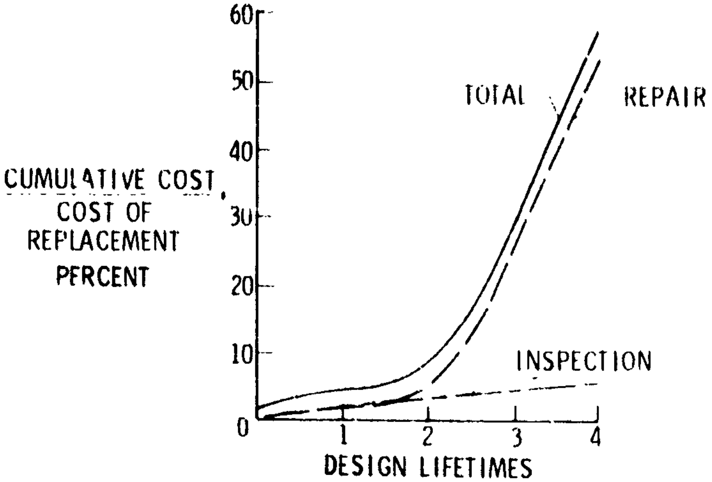
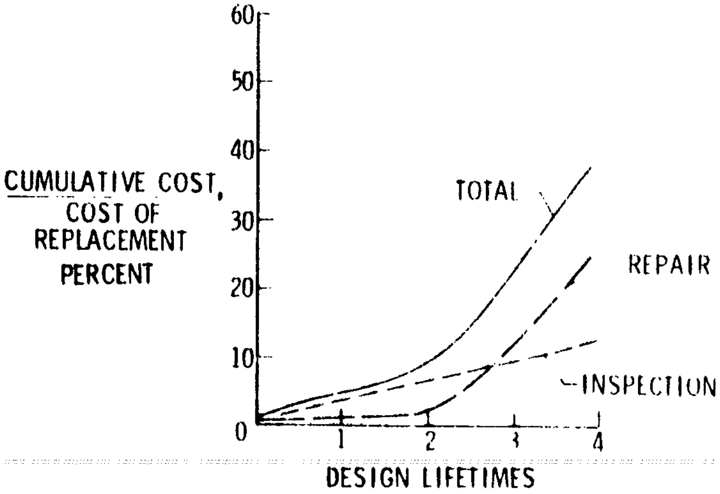


Figure 13.- Relative costs. Inspection interval 2200 flights.



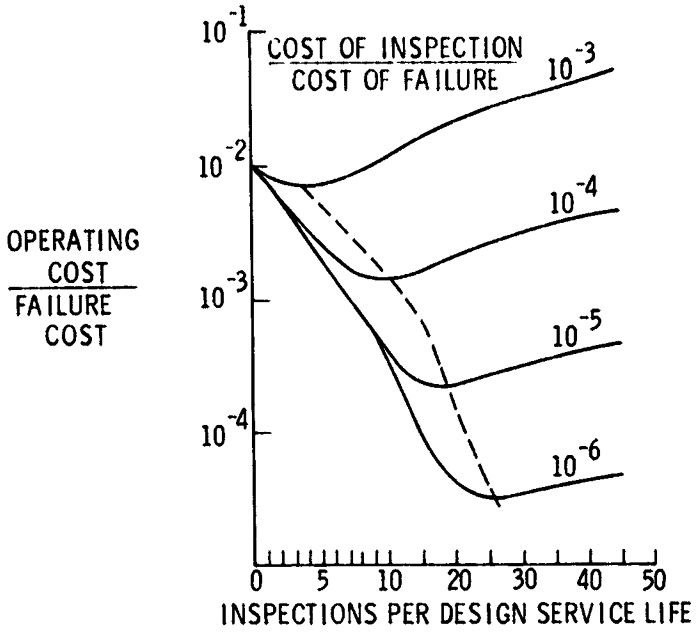


Figure 15.- Optimum number of inspections per lifetime.

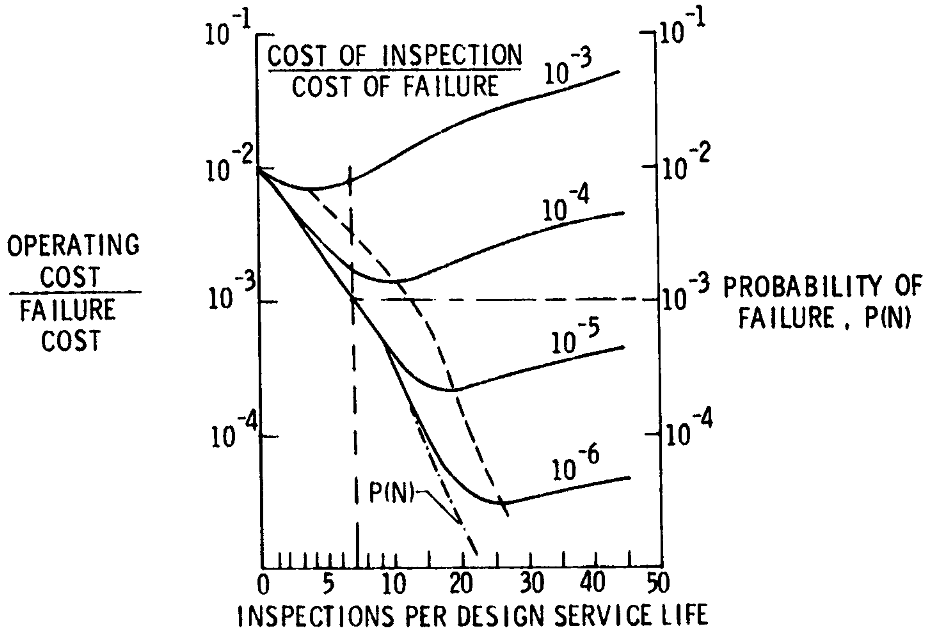


Figure 16.- Optimum number of inspections per lifetime and probability of failure.